

# QCD radiation in $WH$ and $WZ$ production and anomalous coupling measurements

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We study QCD radiation for the  $WH$  and  $WZ$  production processes at the LHC. We identify the regions sensitive to anomalous couplings, by considering jet observables, computed at NLO QCD with the use of the Monte Carlo program **VBFNLO**. Based on these observations, we propose the use of a dynamical jet veto. The dynamical jet veto avoids the problem of large logarithms depending on the veto scale, hence, providing more reliable predictions and simultaneously increasing the sensitivity to anomalous coupling searches, especially in the  $WZ$  production process.

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## I. INTRODUCTION

Higgs production in association with a  $W$  boson is one of the main Higgs boson production mechanisms at the LHC. The LHC experiments did not yet observe the Higgs boson in this channel, but measurements are compatible with the Standard Model (SM) prediction [1, 2].

$VH$  production is the best channel to measure the Higgs decay to  $b\bar{b}$  at the LHC since the leptons from the  $V$  decay can be used for triggering and to reduce the backgrounds. Additionally, it allows the study of the  $VVH$  vertex and possible modifications to it by new physics entering via anomalous couplings (AC). In this article, we will focus on  $WH$  production.

From the theoretical point of view,  $WH$  production has been extensively studied in the literature and results at the next-next-to-leading order (NNLO) in QCD have been provided in Ref. [3] at the total cross section level and in Ref. [4] for differential distributions. AC effects are also a subject of interest [5].

Due to the large gluon luminosity, the fraction of  $WH$  events with additional jets is large. Results for  $WHj$  production at NLO are thus necessary, when one looks at one jet inclusive events as done by ATLAS [2]. Results for this process at NLO QCD have been reported both for  $W$  on-shell production [6] and also including the leptonic decays of the  $W$  [7].

In vector boson pair production processes, it is known that additional jet radiation reduces the sensitivity to AC measurements, results that have been confirmed at NLO in Refs. [8, 9]. To reduce this effect and the sensitivity to higher QCD corrections, the traditional method has been to apply a jet veto above a fixed  $p_T$  [10], which comes with a naive reduction of scale dependence at the total cross section level. A closer look at the scale uncertainties in differential distributions reveals that exclusive samples inherit large scale uncertainties in the tails of the distributions, which are the regions most sensitive to AC

effects. This has also been confirmed using merged samples for  $WW(WZ)$  and  $WWj(WZj)$  using the **LOOPSIM** method [11, 12]. Thus, more sophisticated strategies in current Monte-Carlo driven analysis are needed to gain theoretical control.

In this paper, we study the jet radiation patterns at NLO QCD in  $WH$  and  $WZ$  production. We will show that they have distinctive signatures and we will present a possible strategy to increase the sensitivity in those channels to AC searches. The constructed jet observables are shown at NLO QCD. To accomplish this, we have computed  $WH(j)$  production at NLO QCD, including Higgs and leptonic  $W$  decays, and with the possibility to switch on AC effects. These processes are available in **VBFNLO** [13], a parton level Monte Carlo program which allows the definition of general acceptance cuts and distributions.

The paper is organized as follows. In Section II, the details of our calculation are given. Numerical results, including new strategies to enhance the sensitivity to AC searches will be given in Section III. Finally, in Section IV, we present our conclusions.

## II. CALCULATIONAL SETUP

The  $WZ/WZj$  samples at NLO QCD are obtained from Refs. [14, 15] available in the **VBFNLO** package [13]. The NLO QCD corrections to  $WZ$  production were first calculated in Ref. [16]. To compute the  $WH(j)$  production processes at NLO QCD, we simplified the calculation for  $l\nu_l\gamma\gamma j$  [17] production (from now on called  $W\gamma\gamma j$  for simplicity) as explained below. For more details on the implementation and the checks performed, we refer the reader to Ref. [18]. There, also, comparisons to earlier calculations of NLO QCD corrections to  $WHj$  production [6, 7] are discussed. In the following, we sketch some details of our approach to make this work self-contained.

To compute the LO, virtual and real corrections, we use the effective current approach and the spinor-helicity amplitude method [19, 20] factorizing the leptonic tensor containing the EW information of the system from the QCD amplitude. This allows us to obtain the code for

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the  $WHj$  process from the  $W\gamma\gamma j$  code. For the  $l\nu\gamma\gamma j$  process, first, the generic amplitudes  $W\gamma\gamma j$ ,  $\tilde{W}\gamma j$  and  $\tilde{W}j$  are created. Then, the leptonic decays  $W \rightarrow l^+\nu$ ,  $\tilde{W} \rightarrow l^+\nu\gamma$  and  $\tilde{W} \rightarrow l^+\nu\gamma\gamma$  are included via effective currents, incorporating, in this way, all off-shell effects and spin correlations of the process.

For obtaining the  $WHj$  amplitude, we select the generic  $\tilde{W}j$  amplitude from the  $W\gamma\gamma j$  process, and use the appropriate leptonic current, i.e.,  $\tilde{W} \rightarrow l^+\nu H$ . Decays of the Higgs boson factorize and can be included via branching ratios for the  $H \rightarrow ff$  channels and via effective currents for the  $H \rightarrow 4l$  ones. In this paper, an on-shell Higgs is assumed since off-shell effects contribute at the level of  $10^{-3}$  and thus are negligible. For the  $WH$  process, we proceed in a similar way starting from  $W\gamma$  production [14].

These changes are global in our code and have been cross-checked by comparing the LO and real emission corrections against Sherpa [21, 22]. Agreement at the per mille level was found for integrated cross sections.

Quark mixing effects as well as the possibility to choose between the 4-flavour and 5-flavour scheme are available in the  $WH(j)$  production process, but not for the  $WZ(j)$  channel. Thus, for the sake of comparison, we use a unitary CKM matrix and work in the 5-flavour scheme. Subprocesses with external top quarks are excluded since they are considered to be a different process, but virtual top-loop contributions are included in our calculation. They contribute at the few percent level at most.

Using the Effective Field Theory formalism, the electroweak vertices such as the ones appearing in  $WZ(j)$  and  $WH(j)$  production can be extended to account for beyond the SM physics. These effects are constructed as additional terms in the Lagrangian with dimensionful couplings,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i. \quad (1)$$

We use the basis presented in Refs. [23, 24] to parameterize the AC. In our code, the anomalous trilinear couplings are included via purpose-built Helas routines which are again incorporated via effective currents, e.g. for  $WH(j)$  production, we replaced  $\tilde{W}$ , by  $\tilde{W} = \tilde{W}^{SM} + \tilde{W}^{AC}$ , with  $\tilde{W}^{SM} \rightarrow l^+\nu H$  and  $\tilde{W}^{AC} \rightarrow l^+\nu H$ , the latter via AC contributions coming from dimension 6 operators. The ones needed for the  $WZ(j)$  production process were included in VBFNLO in a dedicated study in Ref. [8]. The specific ones for  $WH(j)$  production were first included in Ref. [25].

While all relevant operators are implemented, we will focus the discussion on the operator

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \quad (2)$$

which does not only induce anomalous  $VVH$  couplings, but also introduces modifications in  $WWV$  vertices and, thus, is severely constrained by LEP data already. The global fit of Ref. [26] bounds the coupling in the range

$f_W/\Lambda^2 \in [-5.6, 9.6] \text{ TeV}^{-2}$ , which is slightly more restrictive than the fit presented in Ref. [27].

In general, the AC contribution is most pronounced at large  $WH$  invariant mass. To measure AC effects, all contributing operators have to be considered, but we will focus and use  $\mathcal{O}_W$  as a typical representative in the following. Note that there are remarkable differences in the coupling structure induced by  $\mathcal{O}_W$  in the  $WWH$  and  $WWZ$  vertex.

To preserve tree level unitarity, we use a dipole form factor of the type

$$F = \left(1 + \frac{s}{\Lambda_{\text{FF}}^2}\right)^{-p}, \quad (3)$$

with  $p = 1$  and  $\Lambda_{\text{FF}} = 2 \text{ TeV}$ , where  $\sqrt{s}$  denotes the  $WH$  or  $WZ$  invariant mass. The value for the form factor scale  $\Lambda_{\text{FF}}$  is derived from requiring that unitarity is preserved in  $VV \rightarrow VV$  scattering using the form factor tool available on the VBFNLO website [28].

### III. NUMERICAL RESULTS

In the following, we present results for the LHC operating at 14 TeV center-of-mass energy for the specific final states  $e^+\nu_e H(j)$  and  $e^+\nu_e \mu^+\mu^-(j)$  and refer to them respectively as  $W^+H(j)$  and  $W^+Z(j)$  production for simplicity. Results for  $W^-H(j)$  and  $W^-Z(j)$  production are very similar.

As input parameters, we use  $M_W = 80.3980 \text{ GeV}$ ,  $M_Z = 91.1876 \text{ GeV}$ ,  $M_H = 126.0 \text{ GeV}$  and  $G_F = 1.16637 \times 10^{-5} \text{ GeV}^{-2}$  and derive the electromagnetic coupling constant and the weak-mixing angle from tree level relations. All the fermions are considered massless, except the top quark with  $m_t = 172.4 \text{ GeV}$ . The resonating propagators are constructed with a constant width, fixed at  $\Gamma_W = 2.098 \text{ GeV}$ ,  $\Gamma_Z = 2.508 \text{ GeV}$  and  $\Gamma_H = 4.277 \text{ MeV}$ .

We use  $\overline{MS}$  renormalization of the strong coupling constant  $\alpha_s$  and the CTEQ CT10 NLO parton distribution functions [29] with  $\alpha_s^{\text{LO(NLO)}}(M_Z) = 0.1298(0.1180)$ . The running of  $\alpha_s$  includes 5 massless flavours, decoupling the top-quark contribution.

As a central value for the factorization and renormalization scale, we choose

$$\mu_0 = \frac{1}{2} \left( \sum_{\text{partons}} p_{T,i} + \sum_{W,Z/H} \sqrt{p_{T,i}^2 + m_i^2} \right), \quad (4)$$

where  $m_i$  denotes the reconstructed invariant mass of the corresponding decay leptons or the on-shell boson.

The jets are clustered using the anti- $k_t$  algorithm [30] with a cone radius of  $R = 0.4$ . To simulate typical detector acceptance, we impose a minimal set of inclusive cuts

$$\begin{aligned} p_{Tl} &> 20 \text{ GeV} & p_{Tj} &> 30 \text{ GeV} & \not{p}_T &> 30 \text{ GeV} \\ |\eta_j| &< 4.5 & |\eta_l| &< 2.5 & R_{l(l,j)} &> 0.4 \\ m_{ll} &> 15 \text{ GeV} & R_{ll} &> 0.4, \end{aligned} \quad (5)$$

TABLE I: Cross sections (in fb) for various jet multiplicities at LO and NLO for  $e^+\nu_e \mu^+\mu^-(j)$  final states, for inclusive and boosted cuts as defined in Eqs. 5 and 6. The relative statistical error is less than  $3 \times 10^{-3}$ .

$N_{\text{jets}}$	inclusive				boosted			
	$W^+Z$		$W^+Zj$		$W^+Z$		$W^+Zj$	
	LO	NLO	LO	NLO	LO	NLO	LO	NLO
0	14.00	16.74			0.492	0.397		
1		11.28	11.31	8.391		1.242	1.248	0.554
2				6.223				1.094

TABLE II: Cross sections (in fb) for various jet multiplicities at LO and NLO for  $e^+\nu_e H(j)$  final states, for inclusive and boosted cuts as defined in Eqs. 5 and 6. The relative statistical error is less than  $3 \times 10^{-3}$ .

$N_{\text{jets}}$	inclusive				boosted			
	$W^+H$		$W^+Hj$		$W^+H$		$W^+Hj$	
	LO	NLO	LO	NLO	LO	NLO	LO	NLO
0	47.08	44.12			4.103	3.188		
1		19.72	20.16	16.12		2.648	2.690	1.889
2				7.16				1.243

where the  $m_{ll}$  cut is applied only to the leptons with opposite sign coming from the  $Z$  boson. To simulate  $VH$  experimental searches, we will also present results for boosted events requiring, additionally,

$$p_{TZ/H} > 200 \text{ GeV}, \quad (6)$$

where  $p_{TZ}$  is the reconstructed transverse momentum of the decay leptons.

The sensitivity to AC is not evenly distributed over phase space. A large contribution to the  $WZj$  cross section comes from events where the  $p_T$  of the  $Z$  boson and the leading jet balance and the  $W$  is soft, or similarly with  $W$  and  $Z$  exchanged. Those events can be considered as EW corrections to  $Vj$  production. Because the invariant mass of the electroweak system is small, they are less sensitive to AC effects. To suppress these events and also to reduce the impact of higher order QCD corrections, a common approach is to apply a jet veto at fixed  $p_T$ . However, this procedure is problematic. The veto introduces terms of the form  $\alpha_s^n \ln^{2n}(s/p_{T,j,\text{veto}}^2)$ , where  $s$  represents a typical scale of the hard process. For large values of  $s$ , this results in a poor control of our perturbative predictions, which may translate into large scale uncertainties of the observables. Note, however, that when studying inclusive samples the uncertainties are frequently underestimated by a naive scale variation. Such features have been extensively discussed for jet vetoes also in the context of NNLO calculations of Higgs-boson production, see e.g. Refs. [31, 32]. Instead of a fixed veto, of jets above a fixed transverse momentum, we will consider a specific dynamical veto in the following which avoids large logarithms by keeping the veto scale proportional to the hard

scale of the process. For  $WV$  production, an effective dynamical jet veto has recently also been discussed in Ref. [33] in the context of observing large electroweak Sudakov logarithms at high transverse momenta.

In Tables I and II, we show the integrated cross sections for different jet multiplicities appearing at different orders of perturbation theory for the inclusive and the boosted set of cuts. One observes that a large fraction of the  $WZ$  production cross section is due to events with jets with  $p_{Tj} > 30 \text{ GeV}$ . With boosted cuts, the NLO sample of  $WZj$  production has twice as many two jet events than one jet events. For  $WHj$  production, jet radiation is also significant. Thus, it is necessary to understand their radiation pattern and how to enhance regions sensitive to AC.

In order to visualize the phase space distributions of jets and weak bosons and their relative hardness, it is necessary to consider their transverse momenta in aggregate. In a  $WVj$  events at LO, transverse momentum conservation implies  $\mathbf{p}_{TW} + \mathbf{p}_{TV} + \mathbf{p}_{Tj} = 0$ , i.e. there are four independent transverse momentum components. Discounting an overall rotation in the transverse plane and anticipating approximate invariance of radiation patterns under rescaling at very high energies, we are left with two parameters describing the essential features of the transverse motion and the relative importance of QCD radiation. These can be taken as the transverse energies of two of the three objects, normalized to the sum for all three, i.e. we consider

$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + \sum_{W,Z/H} E_{T,i}} \quad (7)$$

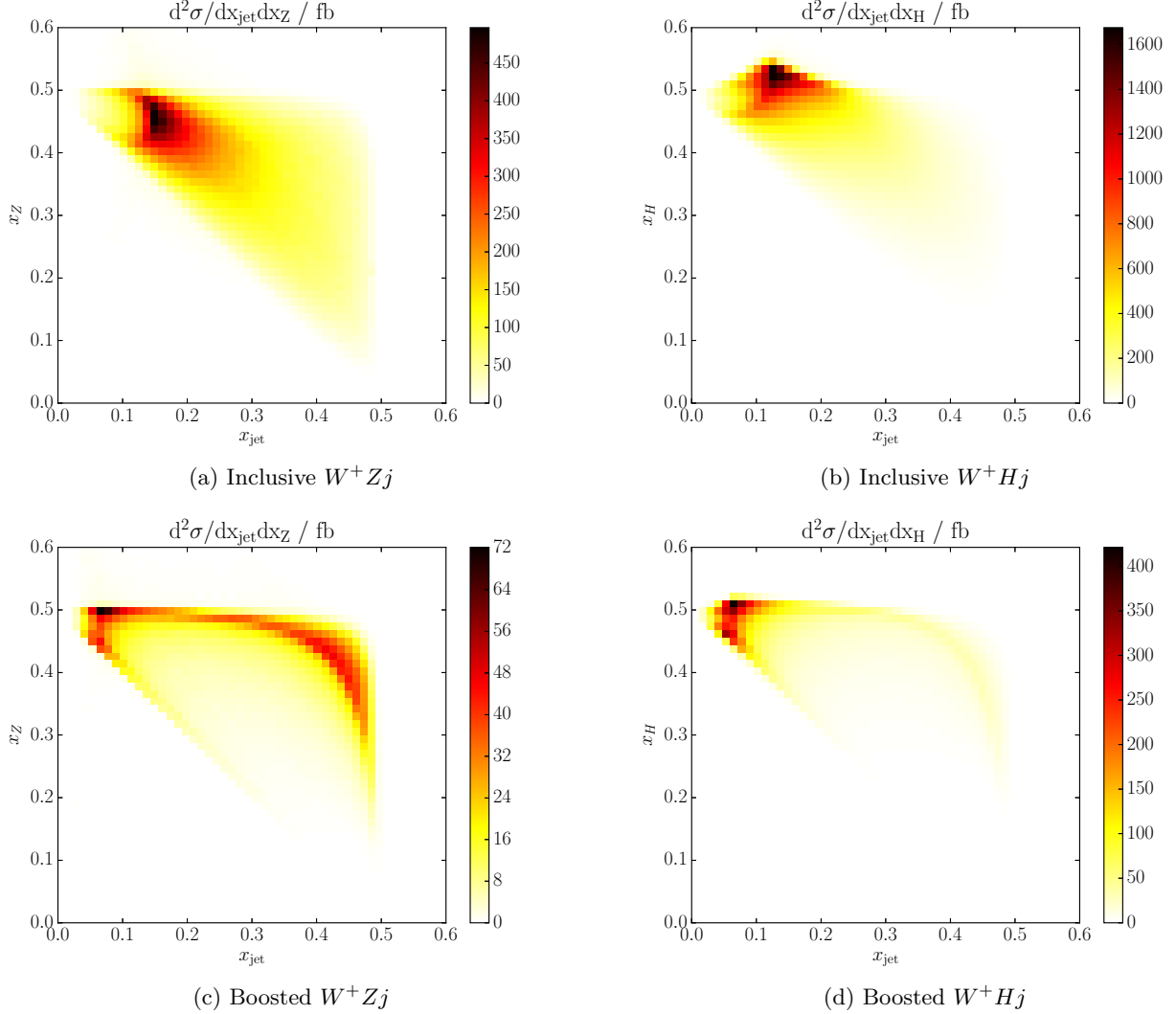


FIG. 1: LO double differential distributions for  $e^+\nu_e \mu^+\mu^-j$  ( $e^+\nu_e Hj$ ) production on the left (on the right) with respect to  $x_{\text{jet}}$  and  $x_Z$  ( $x_H$ ). Inclusive cuts are used in the upper row and boosted cuts ( $p_{T H(Z)} > 200 \text{ GeV}$ ) in the bottom panels.

and, similarly, for  $V \in (W, Z, H)$  we define

$$x_V = \frac{E_{TV}}{\sum_{\text{jets}} E_{T,i} + \sum_{W,Z/H} E_{T,i}}. \quad (8)$$

Obviously,  $x_{\text{jet}} + x_W + x_{Z/H} = 1$ , and in a LO calculation, where a single massless parton forms the jet system which recoils against the other two objects,  $x_{\text{jet}} < 0.5$ .

A similar definition can be constructed using transverse momentum instead of transverse energy. However, in that case,  $x_{\text{jet}}$  is infrared sensitive and problematic in a fixed order calculation, as will be discussed later.

#### $x_{\text{jet}}$ versus $x_{Z/H}$ Distributions

We can use these observables to draw a Dalitz-like 2D plot of  $x_{\text{jet}}, x_{Z/H}$  where phase space regions with soft

EW bosons can easily be distinguished from regions with soft jets. A value close to 0.5 for the  $x_{\text{jet}(H,Z)}$  observable would indicate that the given particle has half of the total transverse energy of the system, recoiling against the rest, while values close to zero indicate that the particle is soft.

In Fig. 1, we show the LO double differential distributions for  $WZj$  and  $WHj$  production with respect to  $x_{\text{jet}}$  and  $x_{Z/H}$  for inclusive (upper row) and boosted cuts (lower panels). On the left,  $WZj$  production is shown and on the right results for the  $WHj$  process, replacing  $x_Z$  by the equivalent  $x_H$  observable.

Already the inclusive sample shows that  $WZj$  production allows for harder jets, while  $WHj$  production is dominated by back-to-back  $WH$  pairs with only soft jets. With the additional boosted cut, the difference is enhanced and one can clearly observe the different radiation patterns of the  $WHj$  and  $WZj$  processes. While in

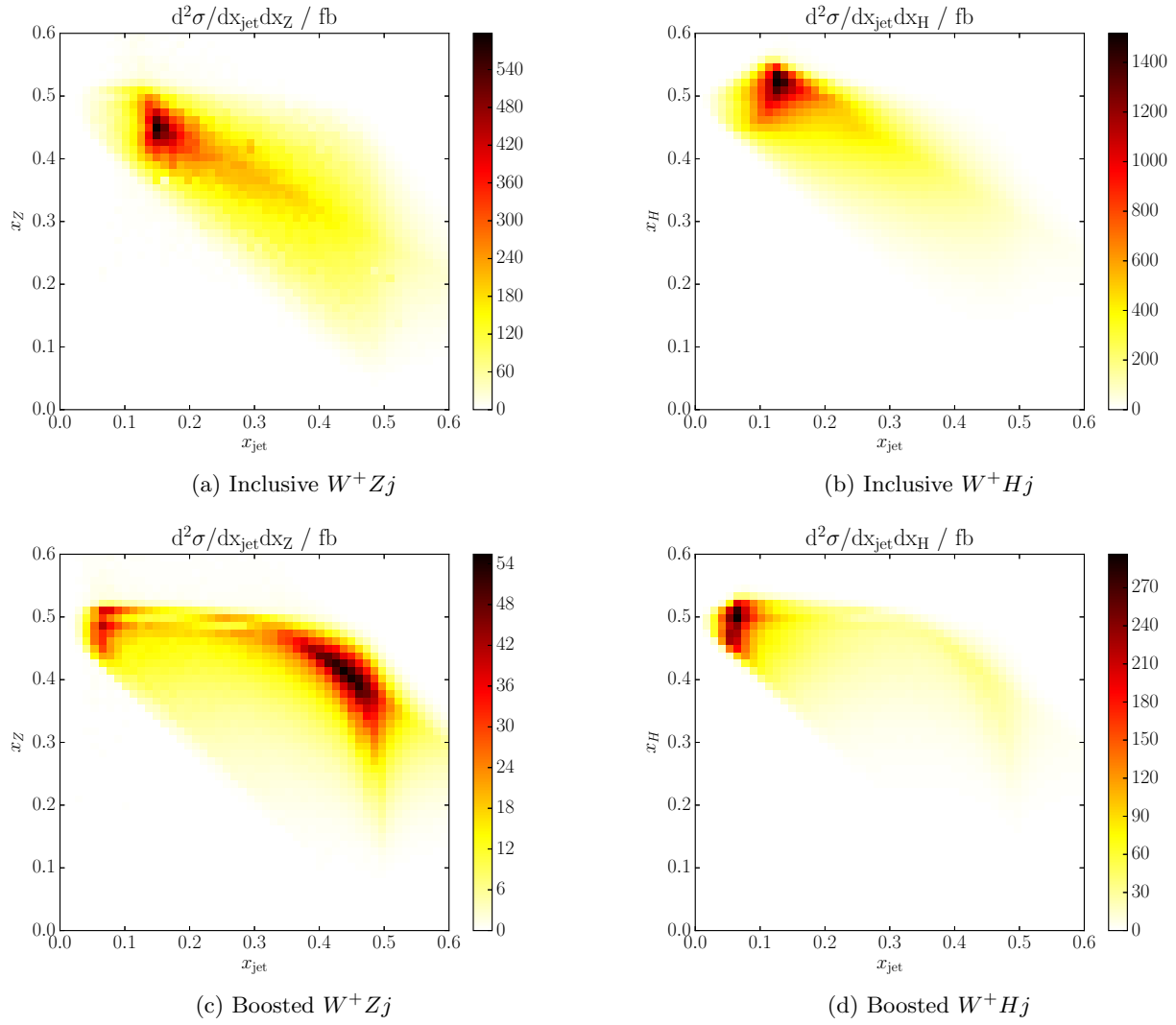


FIG. 2: Same as Fig. 1 but at NLO.

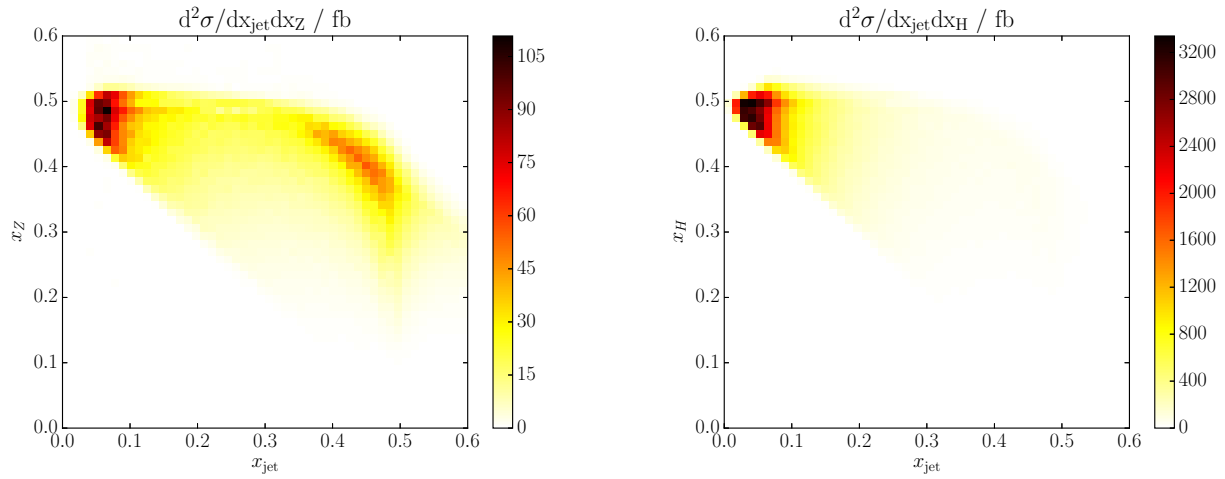


FIG. 3: Same as Fig. 1 but at NLO and with anomalous coupling effects switched on with  $f_W/\Lambda^2 = -10 \text{ TeV}^{-2}$ . Results are shown for the boosted set of cuts for  $e^+\nu_e \mu^+\mu^-j$  (left panel) and  $e^+\nu_e Hj$  production (right panel).

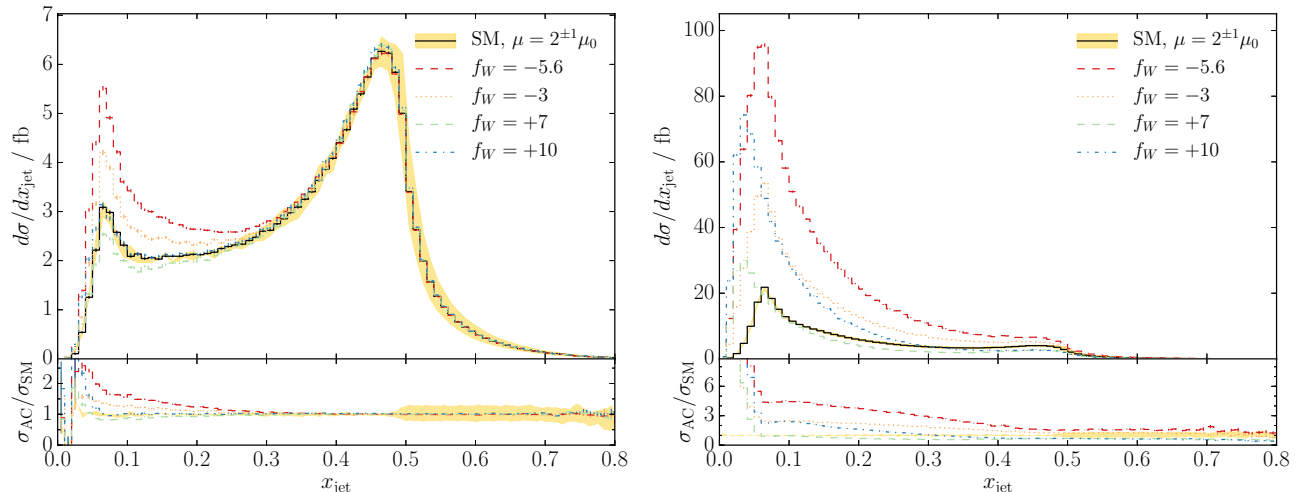


FIG. 4:  $x_{\text{jet}}$  distribution for  $e^+\nu_e \mu^+\mu^-j$  (left) and  $e^+\nu_e H j$  (right) production for different values of AC with boosted cuts at NLO. The yellow band corresponds to the variation of  $\mu = \mu_F = \mu_R$  by a factor of 2. The error bars represent the statistical Monte Carlo error.

$WHj$  production soft QCD radiation is preferred, in the  $WZj$  case there are two equally important phase space regions, those with soft jets at small  $x_{\text{jet}}$  and those with a soft  $W$  boson at large  $x_{\text{jet}}$ . The latter dilutes the sensitivity to AC of this process as will be shown below. The origin of these different radiation patterns is the partial wave decomposition of the  $WH/WZ$  final state.  $WH$  production is mostly restricted to  $J = 1$ , since it arises from a virtual  $W$ , while this is only a small contribution to  $WZ$  production.

Fig. 2 shows the same distributions at NLO. There is an overall small shift to higher  $x_{\text{jet}}$  due to the presence of an additional parton in the real emission contributions. Still the jet dominated and EW dominated phase space regions can be clearly separated.

Note that the  $x_{\text{jet}} = 0.5$  and  $x_Z = 0.5$  borders show unphysical structures at NLO due to phase space restrictions of the 1-parton final states, which affect the Born and virtual corrections. In a final state with only one parton and thus exactly one massless jet after cuts, only  $x_{\text{jet}} < 0.5$  is possible. With two or more partons, the  $x_{\text{jet}}$  definition allows values above 0.5, e.g. for two jets back-to-back with rather soft EW bosons or when there is a parton not clustered into the jets. Because this region is only available to the real emission at NLO and not to the subtraction terms or the virtual corrections, there is an unphysical negative dip just below 0.5. This problem affects an  $x_{\text{jet}}$  definition based on transverse momenta quite strongly, while the definition using  $E_T$  is safer since the masses act as a regulator. In Fig. 2, the dip is barely visible. A parton shower would completely wash out this artefact of the fixed order calculation.

Well below  $x_{\text{jet}} = 0.5$ , these infrared issues are mitigated. In particular, the problem does not affect the region  $x_{\text{jet}} < 0.2$ , which is the region most sensitive

to AC, as is visible in Fig. 3, where we have used  $f_W/\Lambda^2 = -10 \text{ TeV}^{-2}$  as an example. Note in the left panel of Fig. 3 that the relative importance of hard jet events, characteristic of the  $WZj$  process, has diminished considerably once AC are turned on, highlighting the fact that AC effects are more prominent in back-to-back  $WZ$  topologies.

Fig. 4 shows the 1D projection of the differential  $x_{\text{jet}}$  distribution for different values of the AC. For small values of  $f_W/\Lambda^2$ , the dominant term is the interference between SM and AC contribution. Hence, their relative sign is important. For negative couplings there is constructive interference, while for positive values of the coupling the interference is destructive. Thus, first the cross section decreases until the pure AC term outweighs the interference term, which happens for  $W^+Zj$  production at  $f_W/\Lambda^2 \approx +10 \text{ TeV}^{-2}$ . Both Figs. 3 and 4 show that the sensitivity to AC effects is in the low  $x_{\text{jet}}$  region, confirming that hard radiation dilutes the sensitivity to AC searches. We will impose a jet veto requiring  $x_{\text{jet}} < 0.2$  to focus on the region most sensitive to AC. There is small sensitivity to AC up to about 0.3, such that this part of phase space should also be included in experimental searches.

A fixed scale jet veto typically introduces logarithms of the veto scale over the hard process scale. They are visible in form of a widening scale variation band for example in invariant mass or transverse momentum distributions as the energy increases. An indication, that the dynamical jet veto does results in a more reliable theoretical predictions than a veto above a fixed jet transverse momentum, is that the scale variation bands of vetoed cross sections do not grow with energy but stay at a size comparable to the total boosted sample. Such scale variation bands are shown in Figs. 4–6.

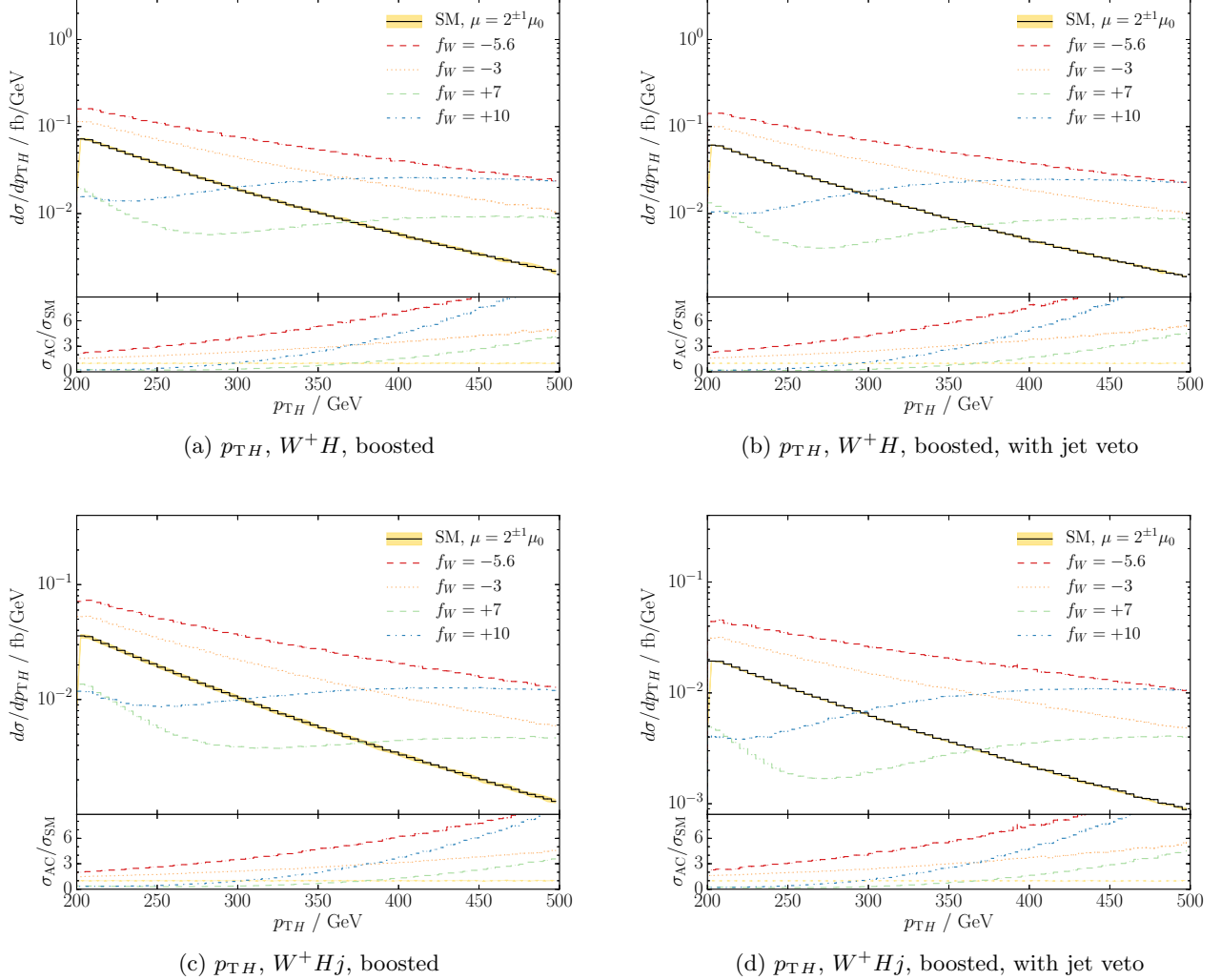


FIG. 5: Differential transverse momentum distribution of the  $H$  boson in  $e^{\pm}\nu_e H(j)$  production for different values of the  $f_W$  parameter with(right) and without(left) a dynamical jet veto. The AC scale is chosen as  $\Lambda = 1$  TeV.

#### Differential Distributions

In Figs. 5 (6), we show transverse momentum differential distributions at NLO for  $W^+H(j)$  ( $W^+Z(j)$ ) production.  $WX$  production at NLO includes 0-jet and 1-jet events, while  $WXj$  production at NLO requires at least one jet with  $p_{Tj} > 30$  GeV.

In Fig. 5, we show the NLO differential distribution of the transverse momentum of the Higgs boson for the boosted sample with (right) and without (left) applying the dynamical jet veto for  $W^+H$  production (upper panels) and for  $W^+Hj$  production (lower panels). The effect of AC is clearly visible in all distributions. As expected, there is only a mild improvement when applying the jet veto since there is little hard jet radiation in this process.

This situation needs to be contrasted with the case of  $WZ$  production, as shown in Fig. 6. In the upper panel,

we consider the transverse momentum distribution of the  $Z$  boson for  $W^+Z$  production at NLO. Distributions are shown for the boosted sample with (right) and without (left) applying the dynamical jet veto. The effect of anomalous couplings is strongly enhanced by the jet veto. Similarly, in the middle and lower rows, we show for  $W^+Zj$  production, the differential distribution of the transverse momenta of the  $Z$  and the  $W$  bosons. Also here one can clearly see the improved AC sensitivity of the vetoed distributions. For  $f_W = -5.6$  TeV $^{-2}$ , in the case of  $p_{TW}$ , the ratio  $\sigma_{AC}/\sigma_{SM}$  increases from 1.3 to 1.5 at 250 GeV and from 1.7 to 2.8 at 500 GeV. For  $p_{TZ}$ , the increases at the same positions are from 1.1 to 1.5 and from 1.3 to 2.4.

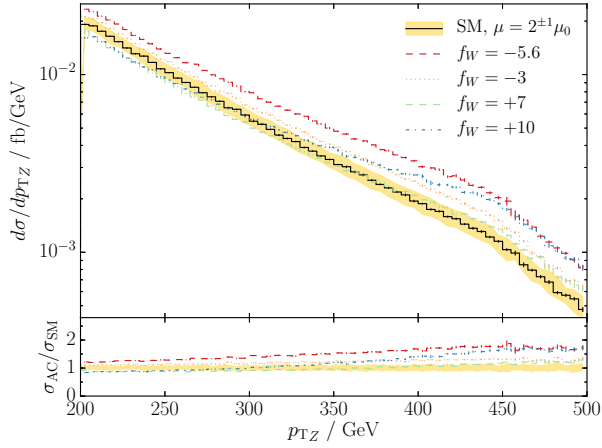
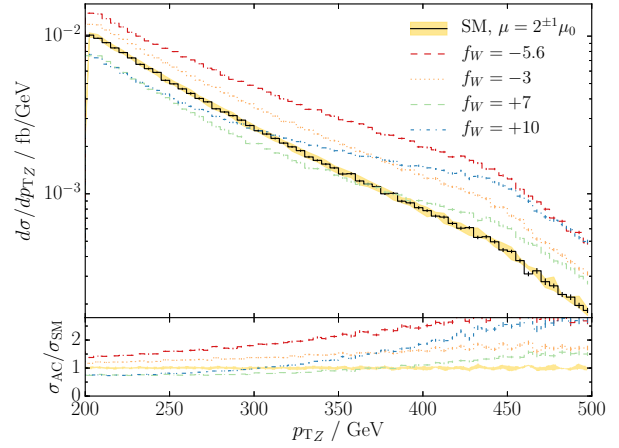
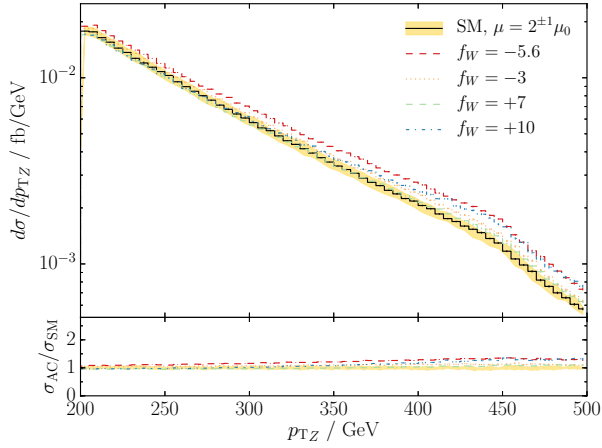
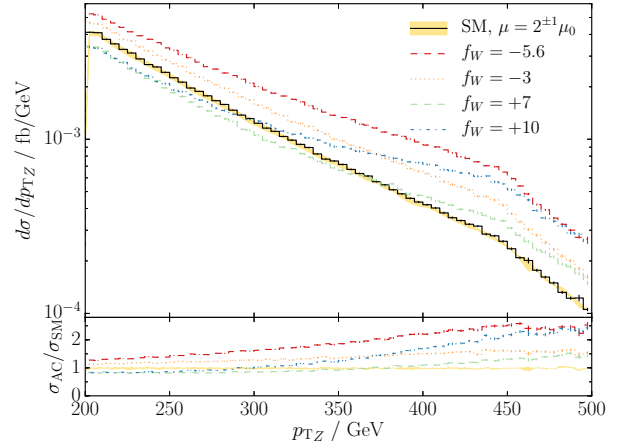
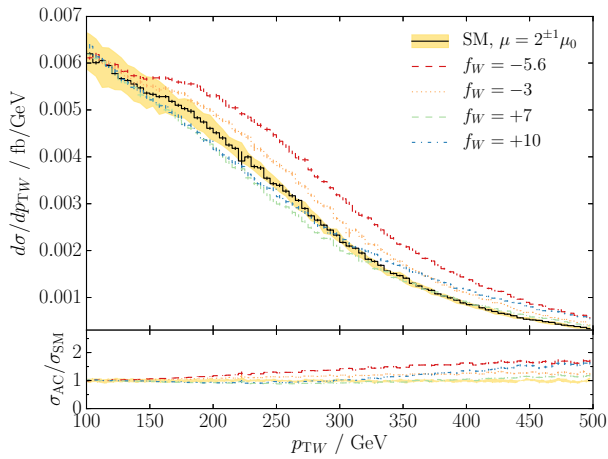
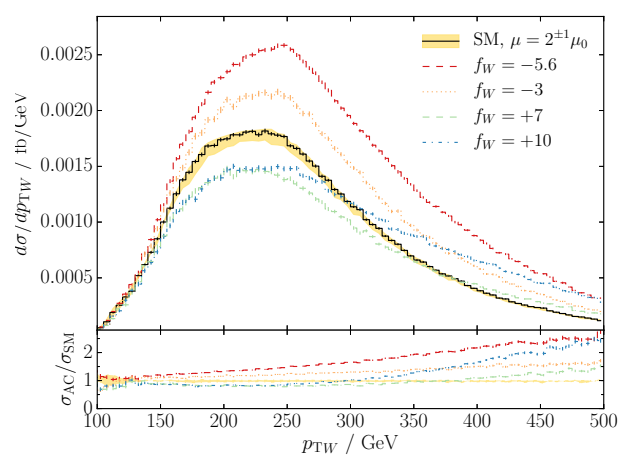
(a)  $p_{TZ}$ ,  $W^+Z$ , boosted(b)  $p_{TZ}$ ,  $W^+Z$ , boosted, with jet veto(c)  $p_{TZ}$ ,  $W^+Zj$ , boosted(d)  $p_{TZ}$ ,  $W^+Zj$ , boosted, with jet veto(e)  $p_{TW}$ ,  $W^+Zj$ , boosted(f)  $p_{TW}$ ,  $W^+Zj$ , boosted, with jet veto

FIG. 6: Differential transverse momentum distribution of the reconstructed  $W$  and  $Z$  boson in  $e^+\nu_e\mu^+\mu^-(j)$  production for different values of the  $f_W$  parameter with(right) and without(left) a dynamical jet veto. The AC scale is chosen as  $\Lambda = 1$  TeV.



## IV. CONCLUSIONS

In this article, the QCD radiation patterns for the  $WZ$  and the  $WH$  production processes have been studied. To accomplish this, we have computed and implemented in VBFNLO, the  $WH(j)$  production process at NLO QCD, including the leptonic decay of the bosons as well as anomalous couplings effects.

Looking at jet observables, we find distinguishable radiation patterns comparing  $WH$  production with  $WZ$  production. While in  $WH(j)$  production soft QCD radiation is preferred, in the  $WZ(j)$  case with boosted cuts there are two equally important phase space regions, those with soft jets and those with one hard vector boson recoiling against a jet and a second soft vector boson. The latter region dilutes the sensitivity of this process to AC. The two phase space regions can be separated quite cleanly by analyzing the Dalitz-like normalized transverse energy fractions defined in Eqs. 7 and 8.

To enhance the sensitivity to AC, a cut on the jet

transverse energy fraction,  $x_{\text{jet}}$ , proves effective. At the same time this dynamical jet veto provides more reliable results than a fixed veto, because it avoids large logarithms involving the veto scale and thus has smaller scale variations.

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